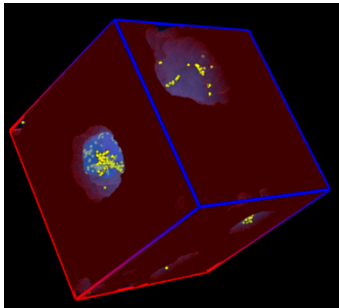

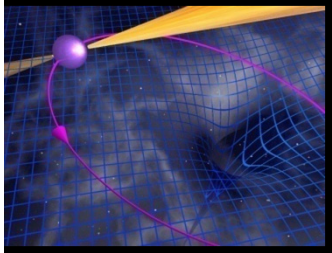

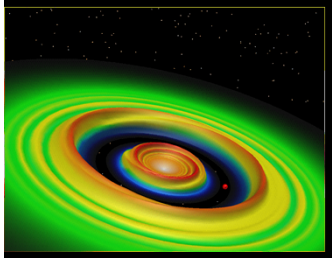

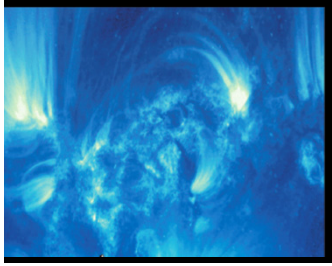

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The Square Kilometre Array

Joseph Lazio

SKA Project Scientist

Jet Propulsion Laboratory, California Institute of Technology

&

SKA Program Development Office

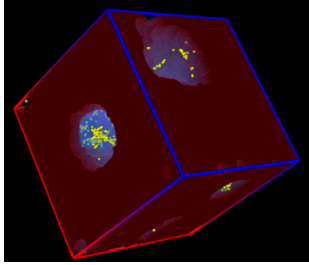
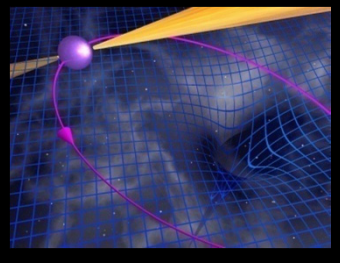
http://www.skatelescope.org/

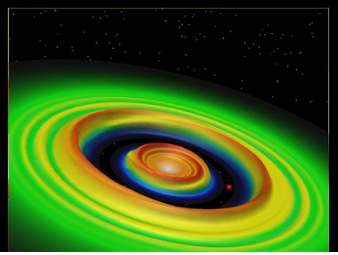
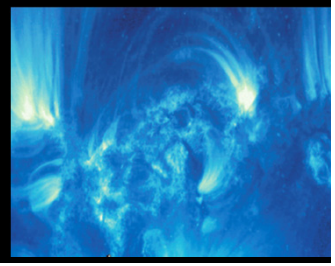
National Aeronautics and Space Administration
Jet Propulsion Laboratory
California Institute of Technology

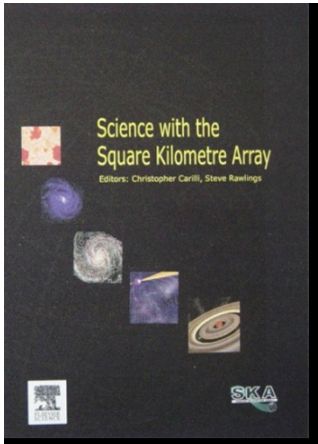
Square Kilometre Array
The Global Radio Wavelength Observatory

- Originally: "Hydrogen telescope"
  - Detect H I 21-cm emission from Milky Way-like galaxy at $z \sim 1$

- SKA science much broader
  - $\Rightarrow$ Multi-wavelength, multi-messenger
- On-going technical development
- International involvement



21st Century Astrophysics

20th Century: We discovered our place in the Universe

21st Century: We understand the Universe we inhabit

Do We Understand the Extremes of the Universe?

- Gravity
  - Can we observe strong gravity in action?
  - What is dark matter and dark energy? (dark energy and BAOs with H I galaxies)
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  - Is there evidence for life on exoplanets? (SETI)

Origins
First Light
Galaxy Evolution
Astrobiology

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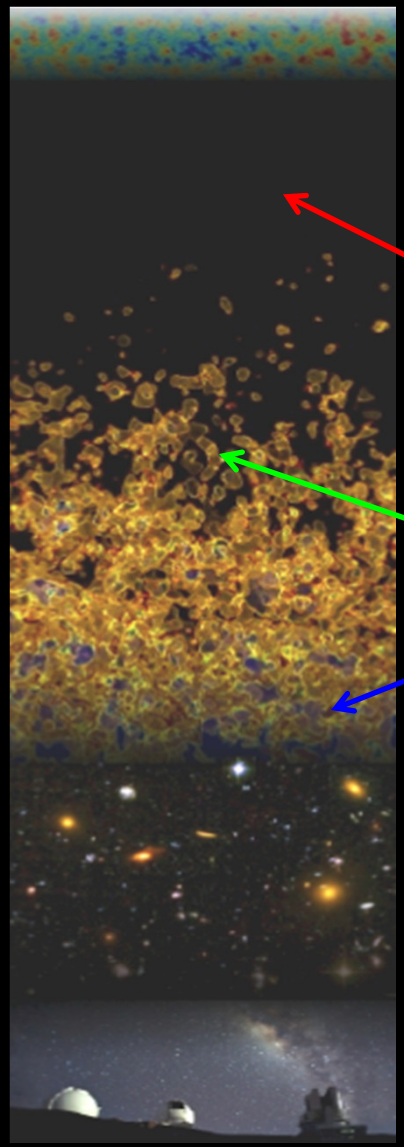
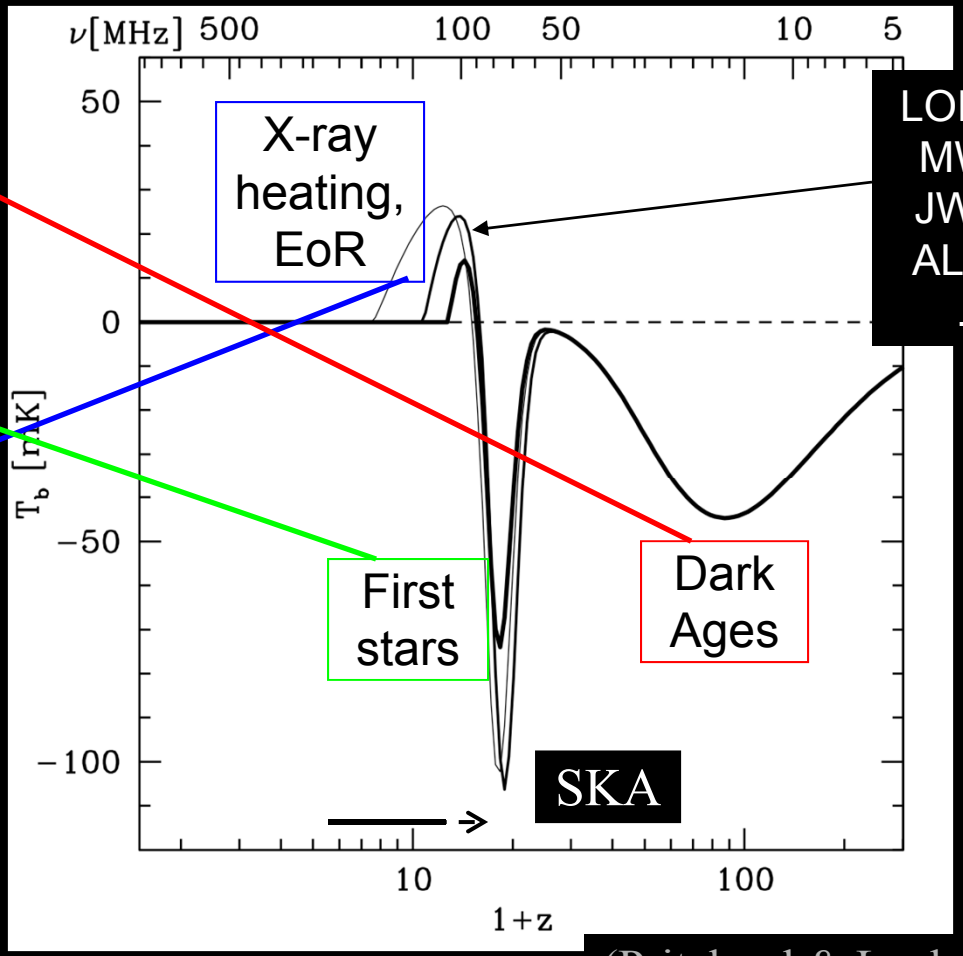
Evolution of the Universe



H I brightness temperature signal (w.r.t. CMB)



LOFAR, MWA, JWST, ALMA, …

(Pritchard & Loeb 2008)

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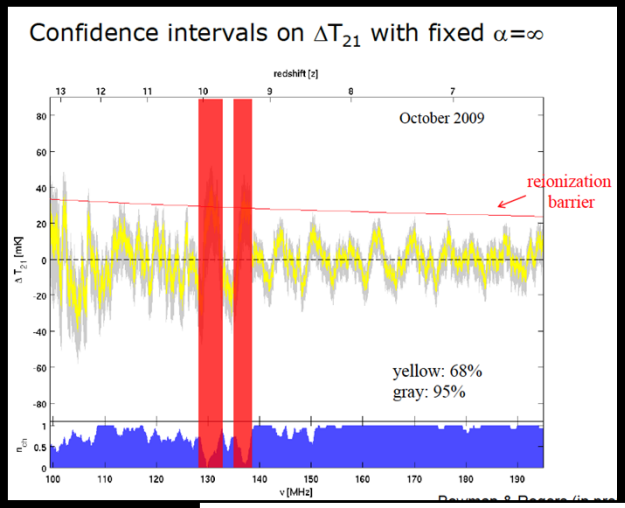
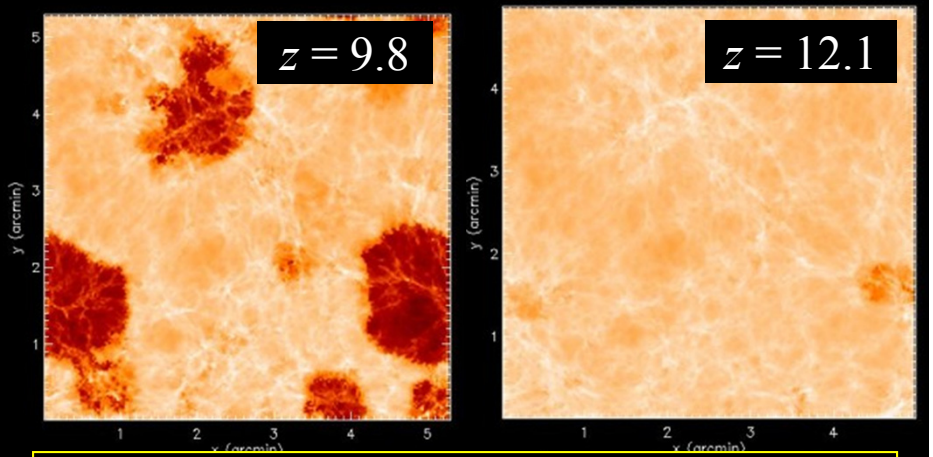
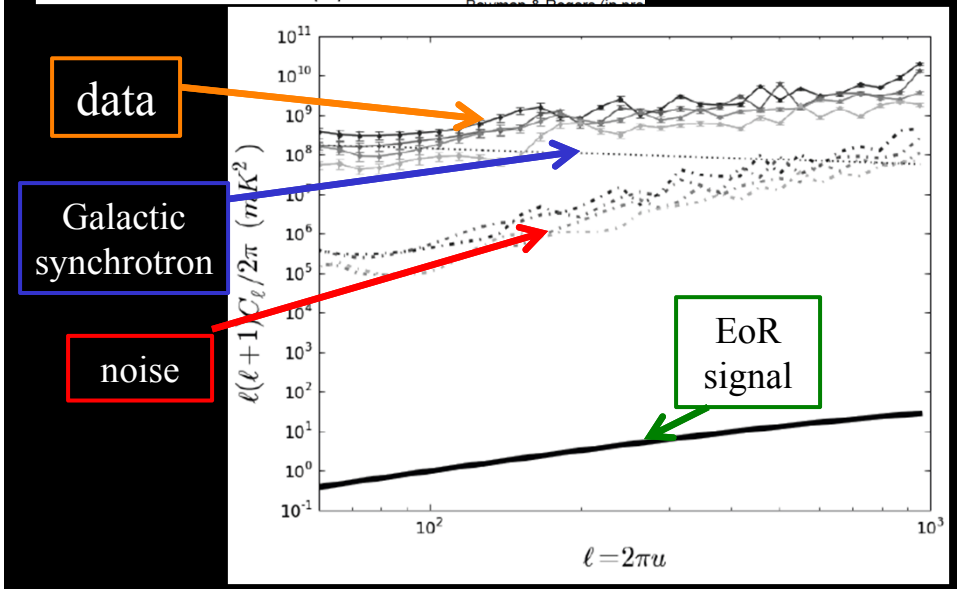
Epoch of Reionization



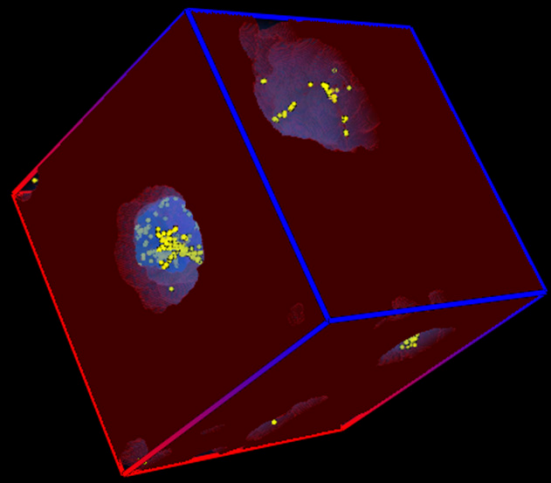
Bowman et al. 2008



SKA objective: Image the IGM transition in the H I (21-cm) line



Parsons et al. 2009; arXiv:0904.2334



Video at
`http://home.fnal.gov/~gnedin/`
Furlanetto et al.; Gnedin

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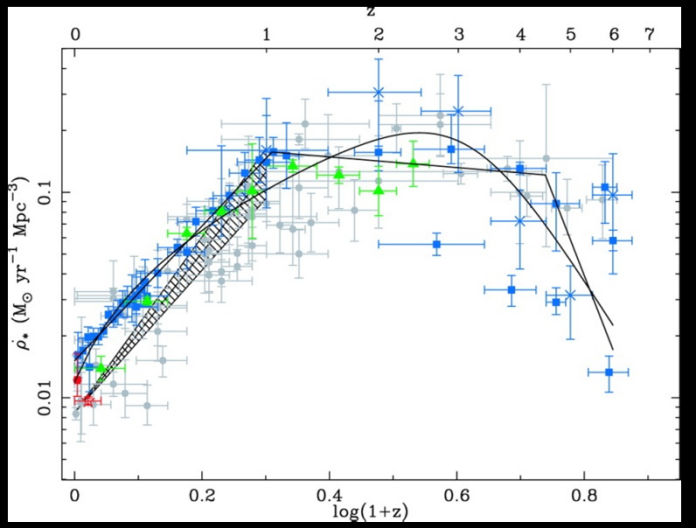
Galaxy Assembly
Stars *and* Gas

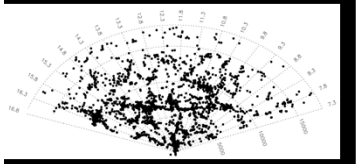
- Stellar "downsizing" since $z \sim 1$
- … but gas content unchanging!
- Gas content and dynamics becoming critical part of simulations.

stars →

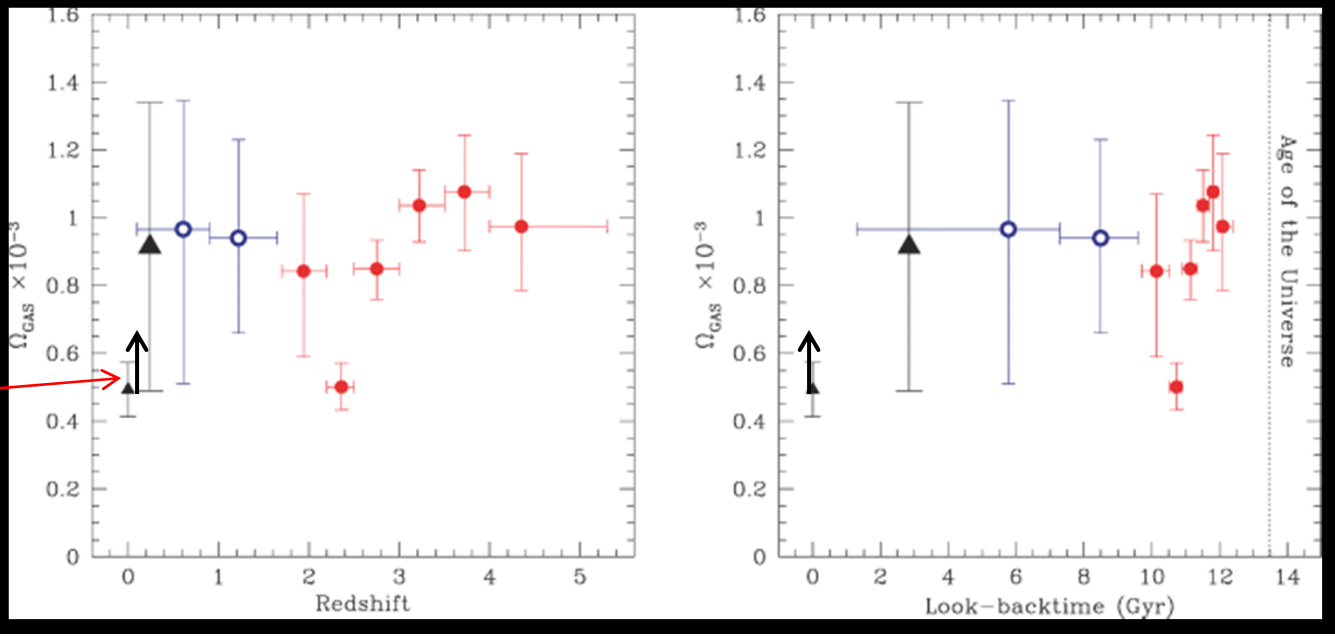


gas ↓

Hopkins & Beacom



HIPASS (Parkes), ALFALFA (Arecibo)



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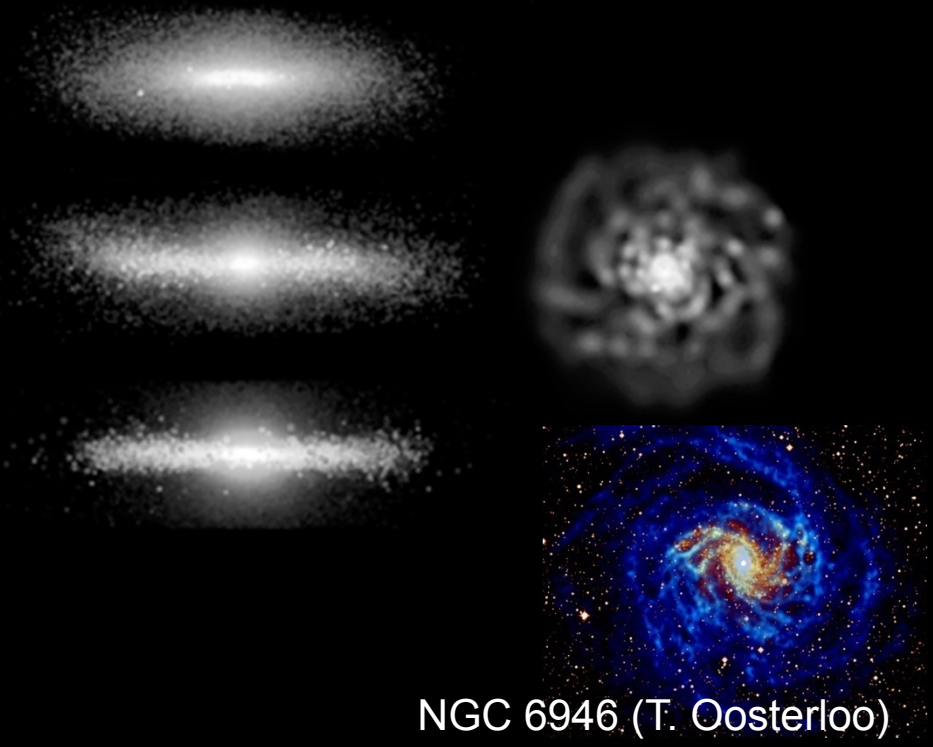
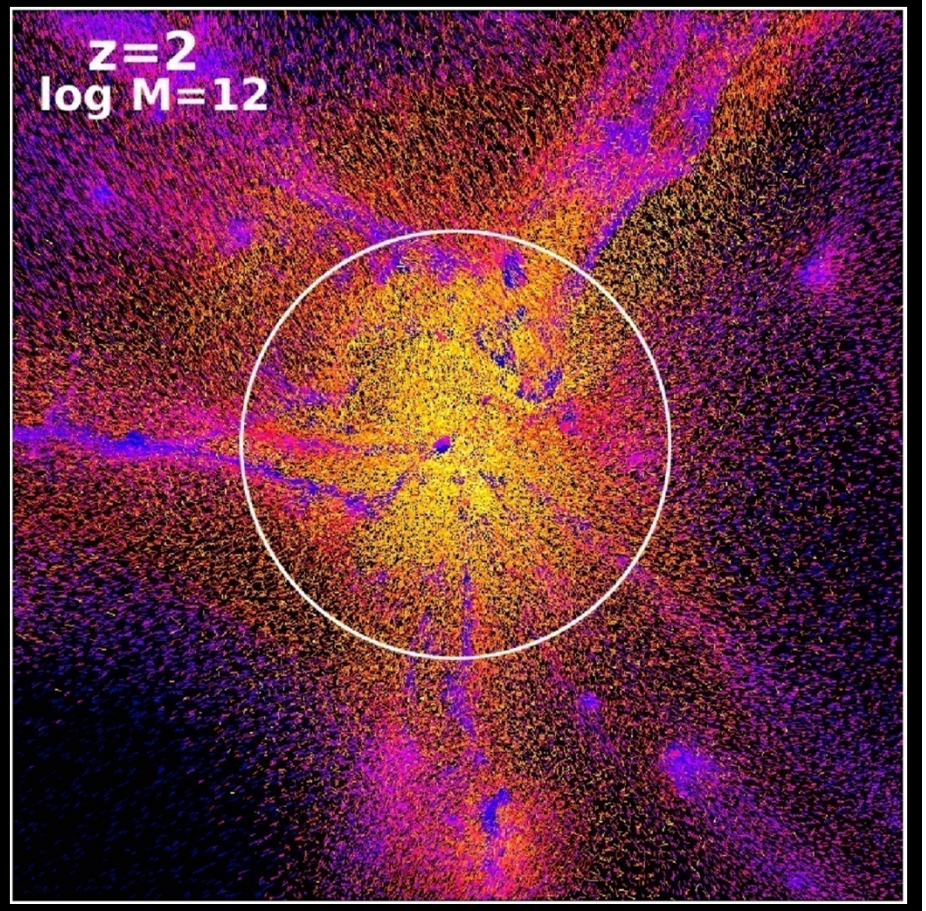
Galaxy Assembly
Stars *and* Gas

- Gas content and dynamics becoming critical part of simulations.
- Astronomy is an *observational* science.



NGC 6946 (T. Oosterloo)



Keres et al.

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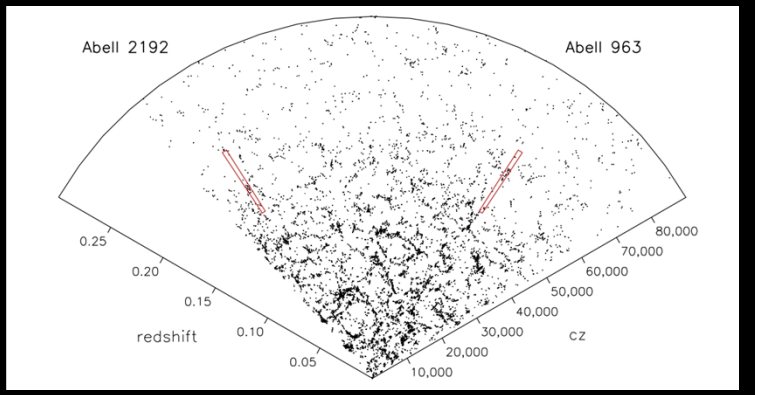

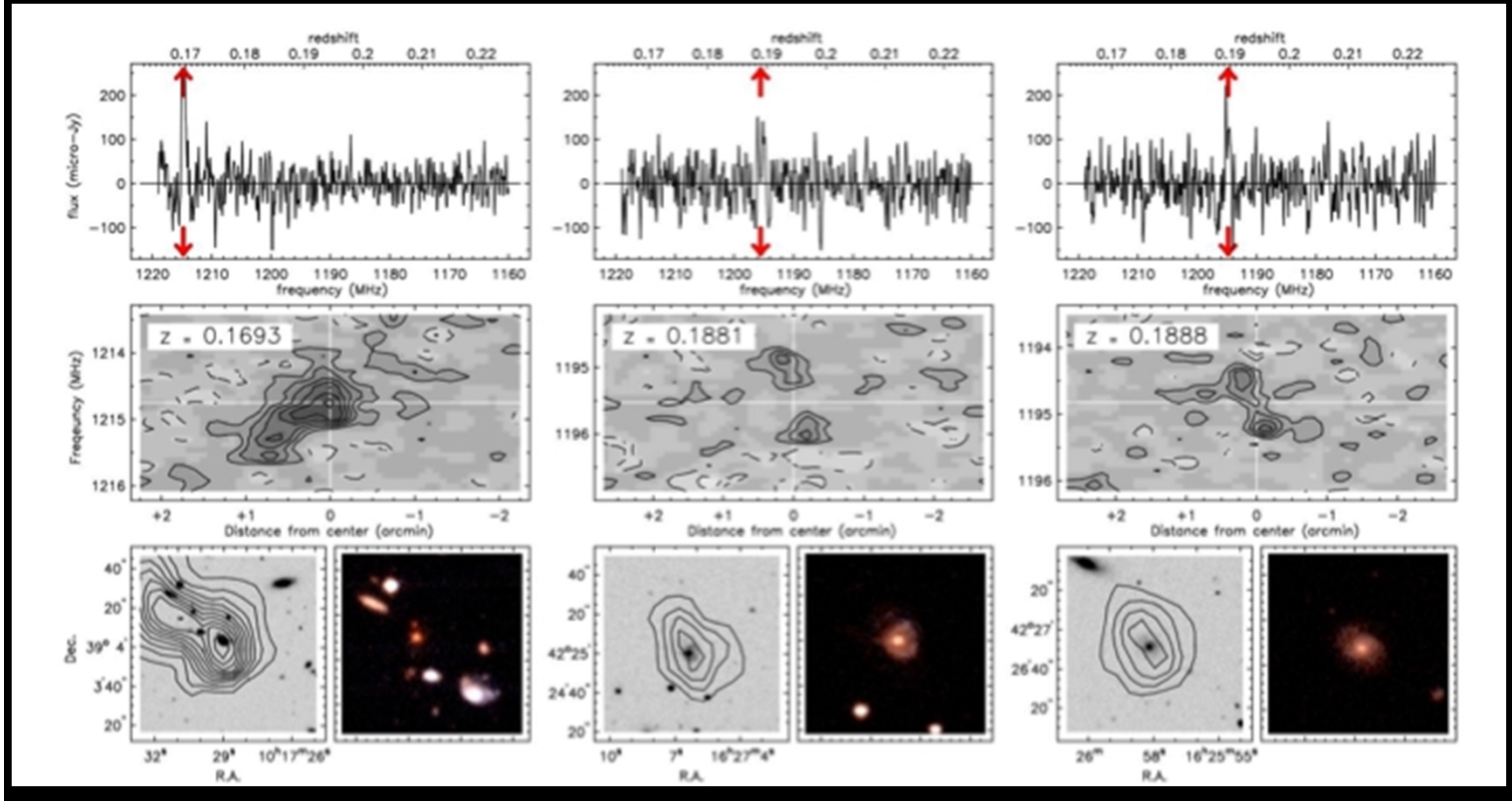

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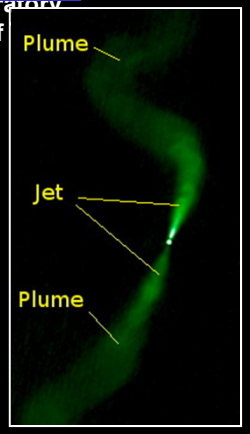
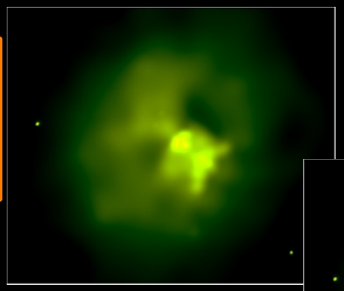
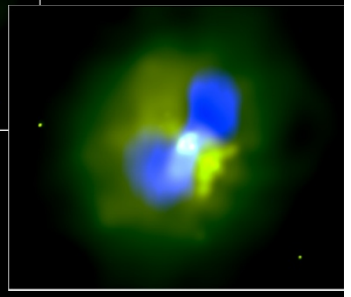
… and Feedback



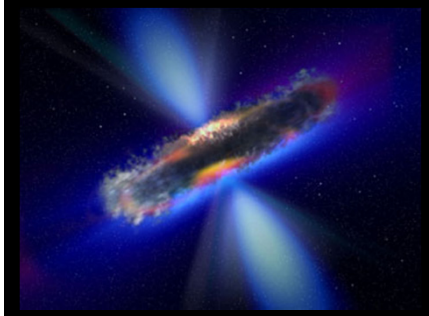
Radio Jet activates

Heats X-ray gas

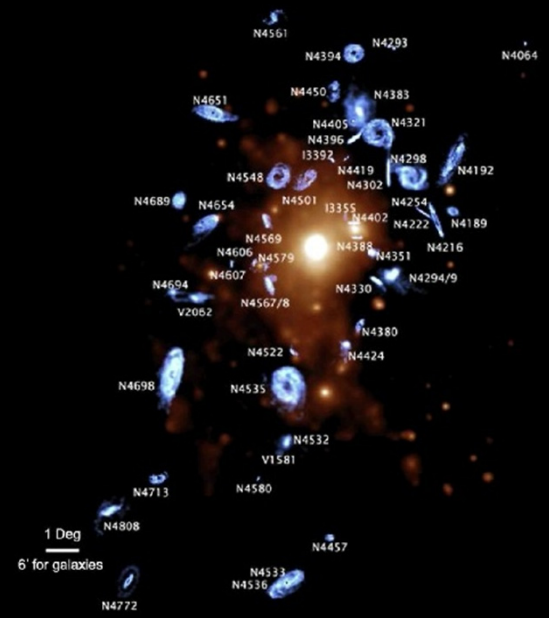




Offset X-ray cooling



BH accretion



BH stops accreting

X-ray cooling

RG is quiescent

Clarke,
Feretti

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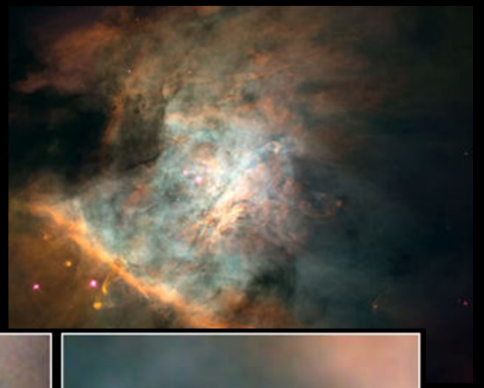
Astrobiology at Long Wavelengths

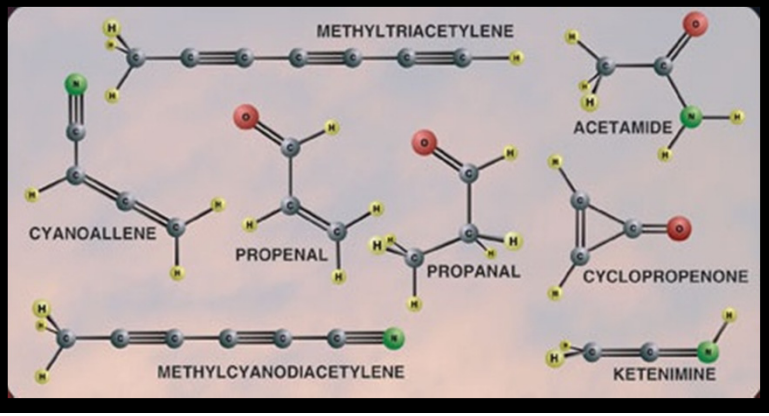


$\lambda > 1$ cm

- Not affected by dust
- Complex molecules have transitions at longer wavelengths
- "Waterhole" (1.4–1.7 GHz)
- Magnetically-generated emissions from extrasolar planets

Protoplanetary Disks
Orion Nebula
HST · WFPC2

PRC95-45b · ST ScI OPO · November 20, 1995
M. J. McCaughrean (MPIA), C. R. O'Dell (Rice University), NASA



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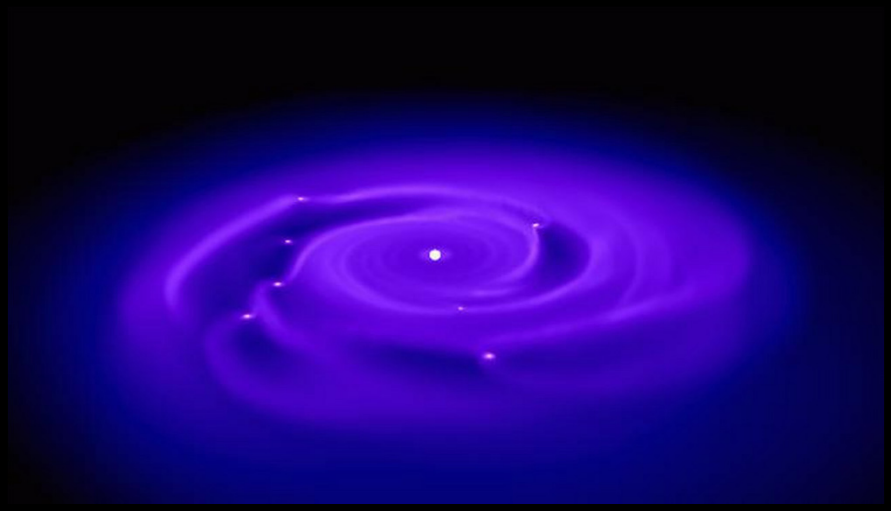
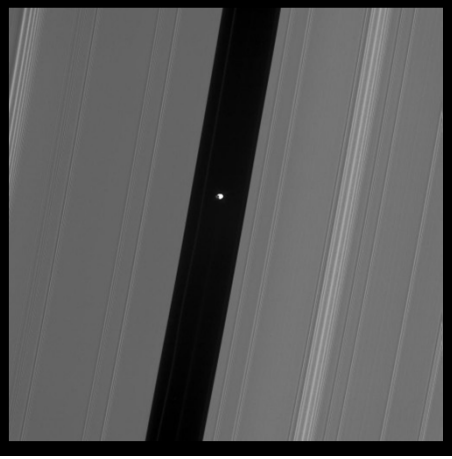
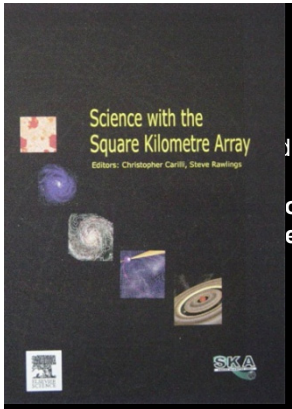
Protoplanetary Disks

- 1 cm wavelength probes thermal radiation from "pebbles"
- Disks optically thin
- Image nearby protoplanetary disks
  - Cf. ALMA, < 700 μm
  - mas resolution @ 1 cm is routine, all that's lacking is *sensitivity*
- Orbital period @ 1 AU ~ 1 yr
  - ➢ movies



Video at
`http://imp.mcmaster.ca/images/Planet_movie1.mpg` (Mayer)





21st Century Astrophysics

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- Gravity
  - Can we observe strong gravity in action? (radio pulsar tests of GR)
  - What is dark matter and dark energy? (dark energy and BAOs with H I galaxies)
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- Strong force

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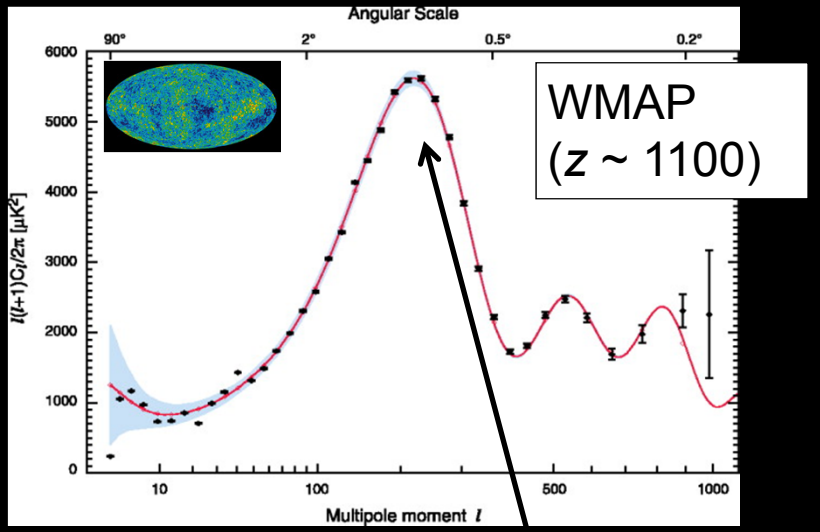
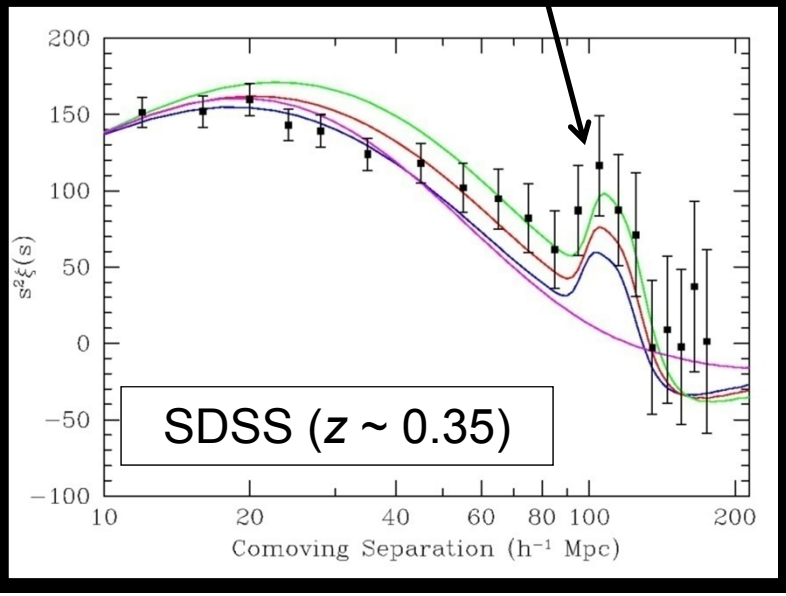
Fundamental Physics
- Dark Energy
- GR & BHs
- Strong Force

Baryon Acoustic Oscillations

Remnant of plasma acoustic oscillations in early Universe

- $D_A(z)$ = angular size distance as a function of redshift
- ~ 100 h^{-1} Mpc "standard ruler"
- Measures expansion rate of Universe





Fundamental Physics
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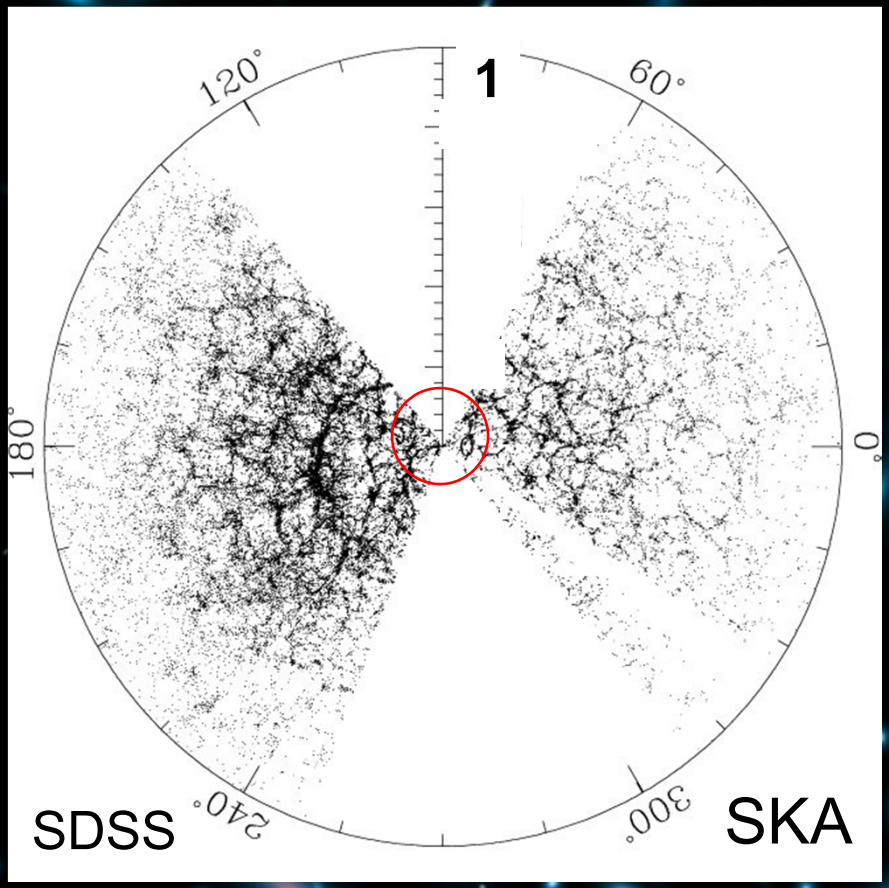
SKA: Stage IV BAOs



- Next-generation goal:
  - Survey large volume
  - Slice into redshift bins
  - Detect BAOs in each z bin
- SDSS surveyed ~ 1 Gpc^3
  - One redshift bin ~ 0.35
- SKA targeting 100 Gpc^3 ($z > 1$)
- H I galaxies
  - Intrinsically spectroscopic survey
  - Different biases than LSST, WFIRST/Euclid

Fundamental Physics
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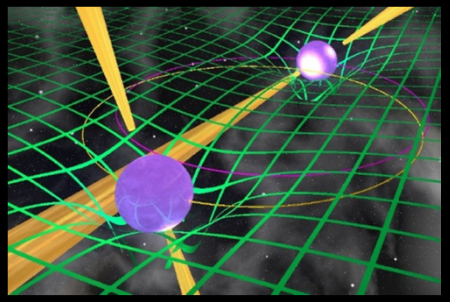
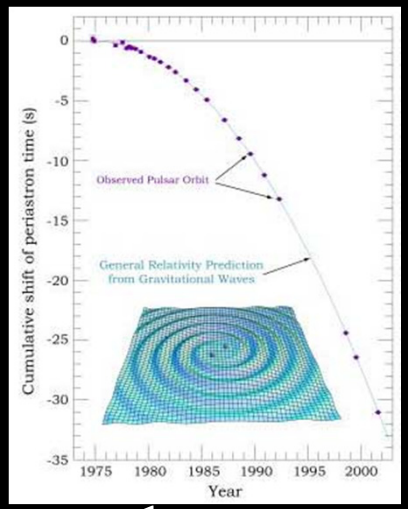
- GR & BHs
- Strong Force

Did Einstein Have the Last Word on Gravity?

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = 8\pi G T_{\mu\nu}/c^4$$

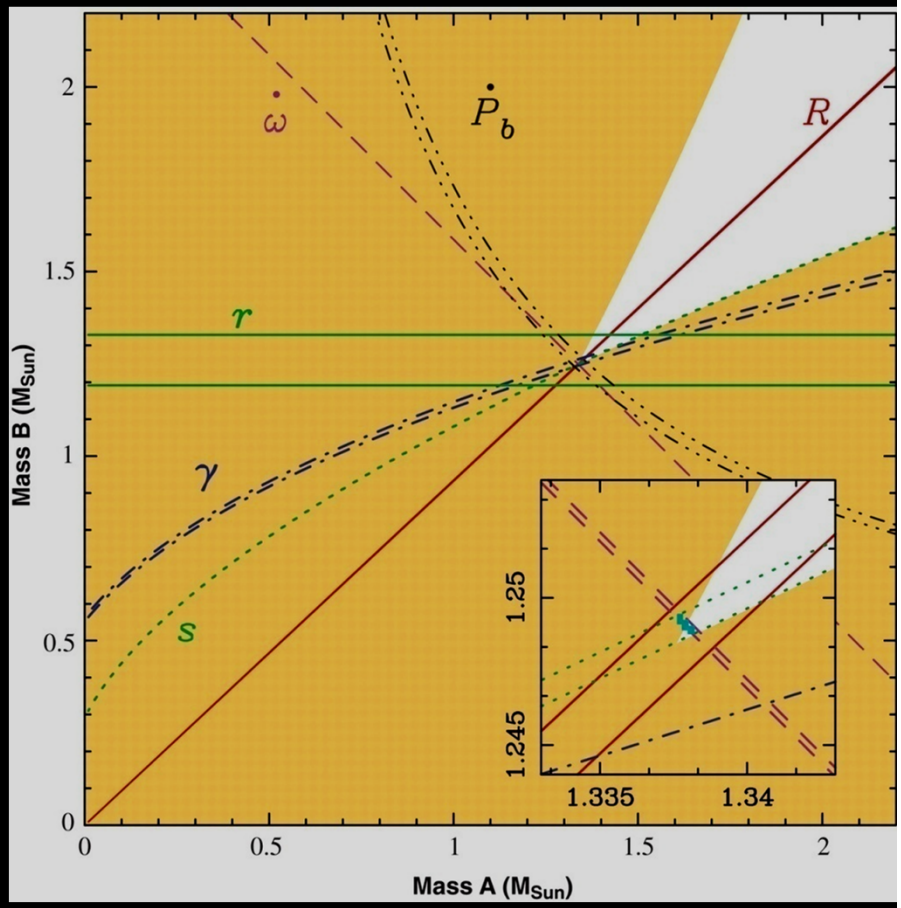




- Relativistic binaries probe
  1. Equivalence principle
  2. Strong-field tests of gravity
- Only neutron star-neutron star binaries known

? Black hole-neutron star binaries?

PSR J0737–3039



Kramer et al.

Fundamental Physics
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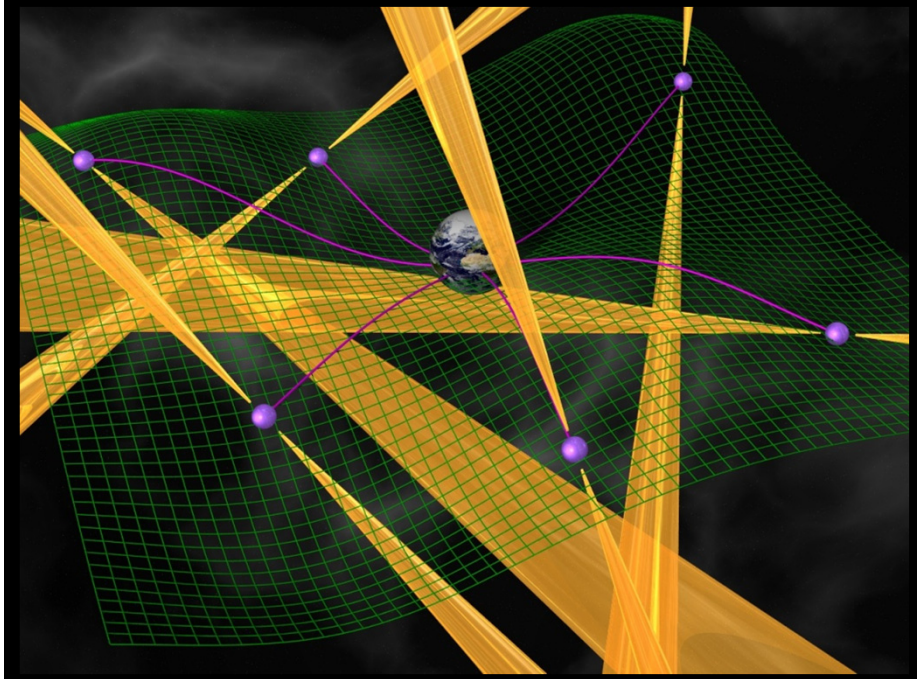
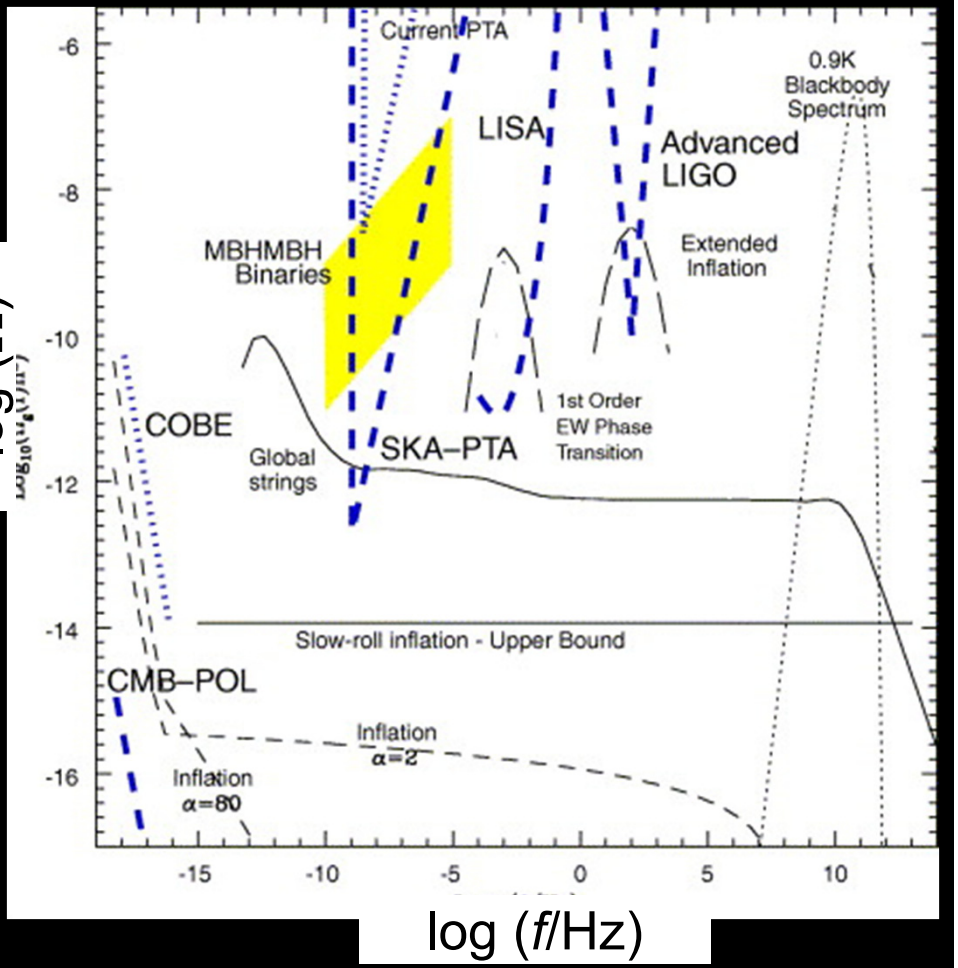
SKA: Gravitational Wave Detector



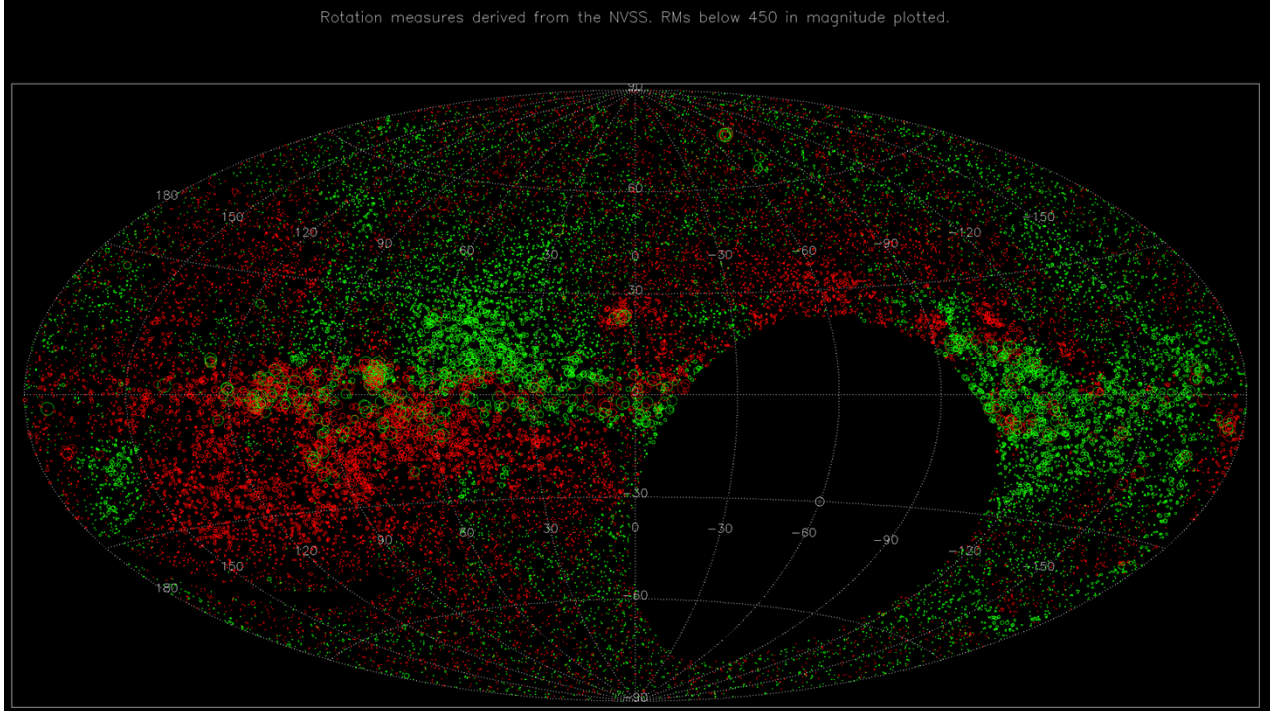


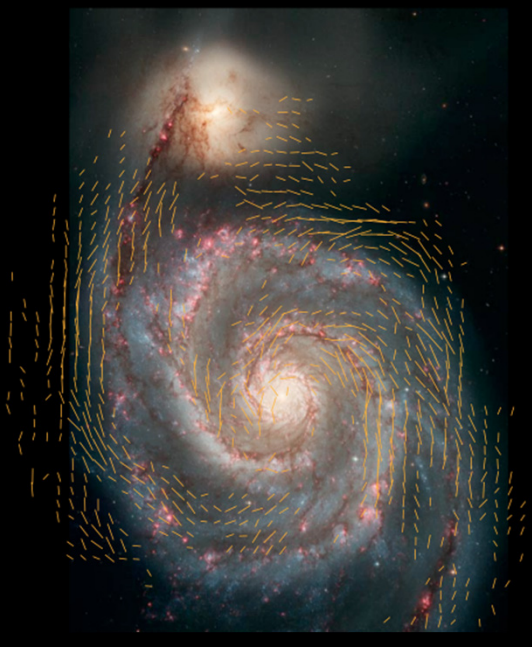
Test masses on lever arm
- Pulsar Timing Array = freely-falling **millisecond** pulsars
- LIGO = suspended mirrors
- LISA = freely-falling masses in spacecraft

Fundamental Physics
- Dark Energy
- Gravity
- Magnetism

Origin & Evolution of Magnetic Fields

- Magnetic fields are fundamental, but poorly constrained
  - Affects galaxy, cluster evolution?
  - Affects propagation of cosmic rays in ISM and IGM
- All-sky rotation measure surveys provide B fields along lines of sight





Fundamental Physics
- Dark Energy
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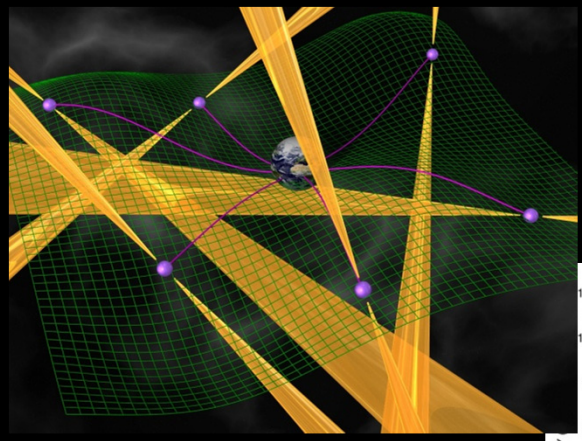
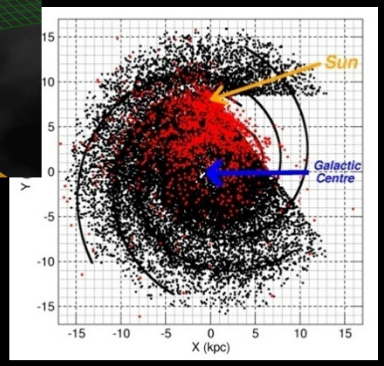
Fundamental Forces

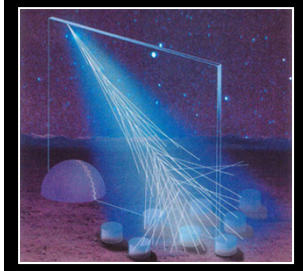
SKA: gravity, strong force, magnetism

$$G_{\mu\nu} + \Lambda g_{\mu\nu} = 8\pi G T_{\mu\nu}/c^4$$

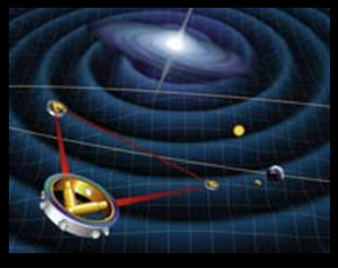


X- and γ-rays: gravity, strong force

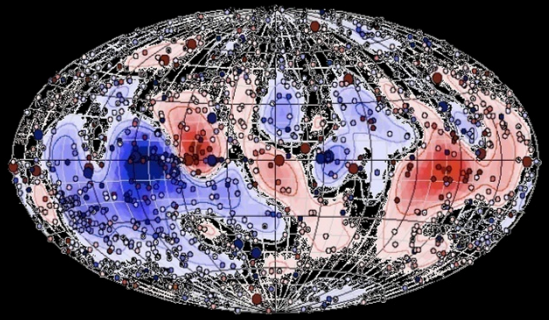




Auger: cosmic-ray propagation



LIGO, LISA: gravity



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21st Century Astrophysics

Fundamental Forces and Particles

- Gravity
- Magnetism
- Strong force

Origins

- Galaxies and the Universe
- Stars, Planets, and Life

"The Universe is patiently waiting for our wits to grow sharper."

Photon frequency/wavelength/energy

Time

Polarization

Sensitivity

Field of View

Angular Resolution

The Dynamic Radio Sky

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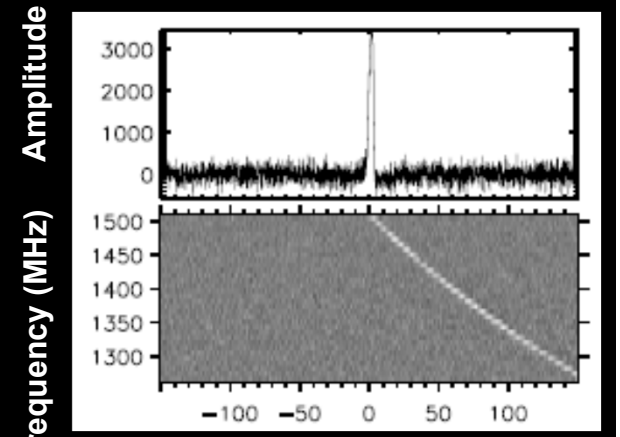
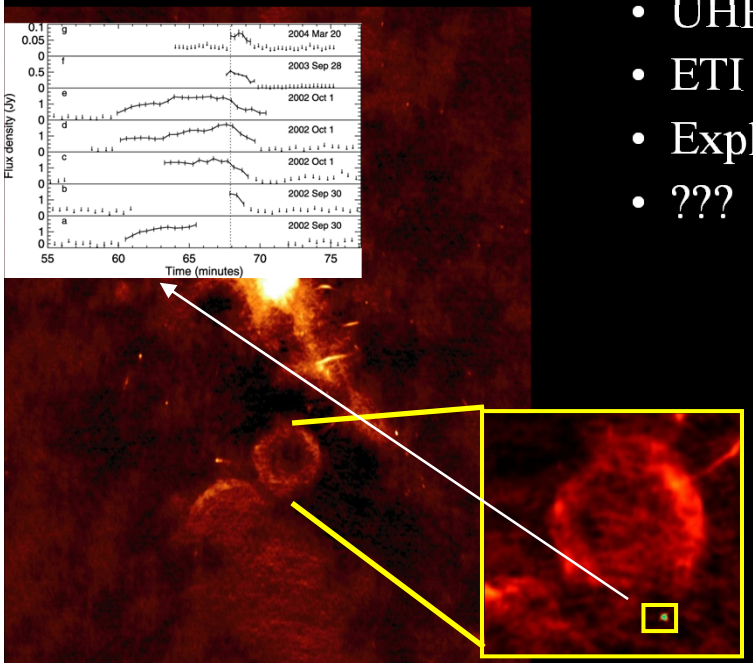
Jet Propulsion Laboratory
California Institute of Technology

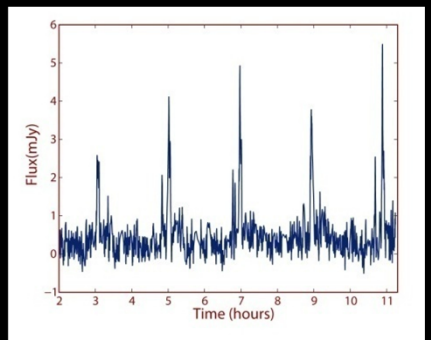
- Neutron stars
  - Magnetars
  - Giant pulses
  - Short GRBs?

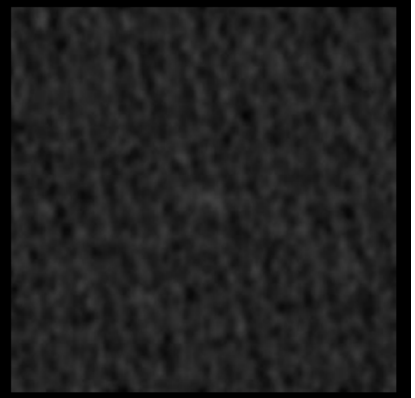
- GRBs (γ-ray loud; γ-ray quiet?)
  - Afterglows
  - Prompt emission?
- Sub-stellar objects
  - Brown dwarfs
  - Extrasolar planets?
- Microquasars
- Scintillation
- UHECRs
- ETI
- Exploding black holes
- ???



Rotating Radio Transients (RRATS)







Pulsating Brown Dwarfs

Dynamic Radio Sky

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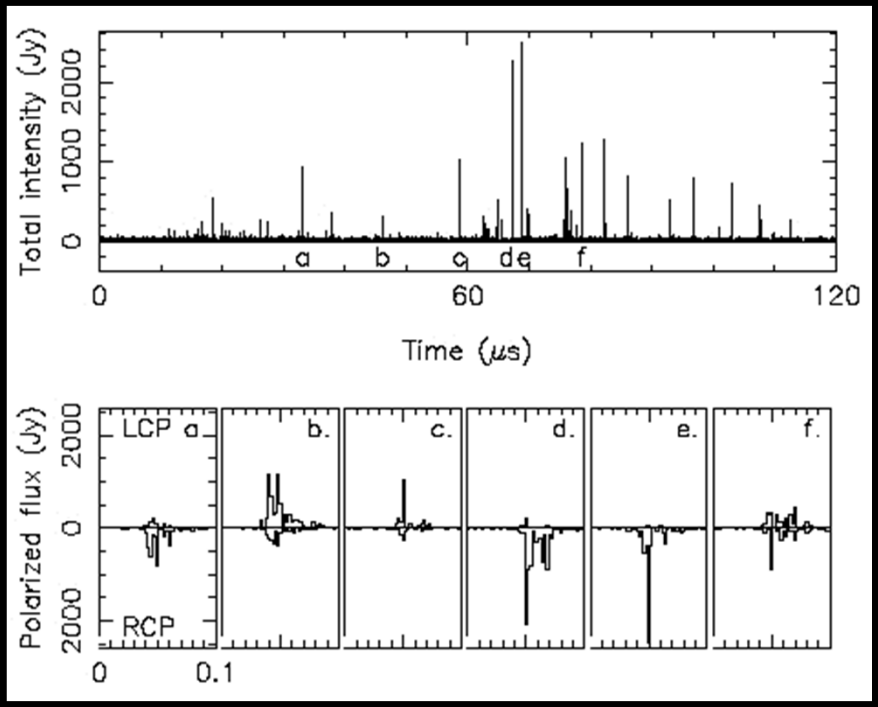
All-sky surveys

(3C, NVSS, …)

+

(?)



Nano-second pulses from the Crab pulsar, from Arecibo

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Jet Propulsion Laboratory
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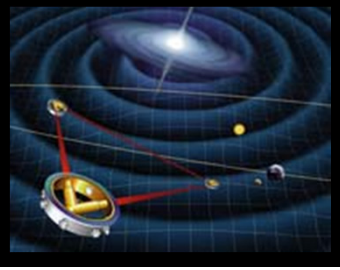
Dynamic Radio Sky and 21st Century Astrophysics

SKA

Optical survey telescopes

X- and γ-rays



LIGO, LISA

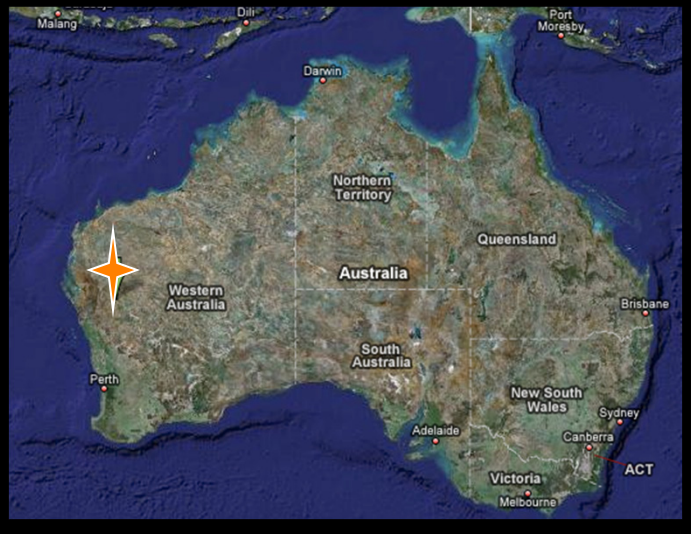
Transient sources are necessarily compact

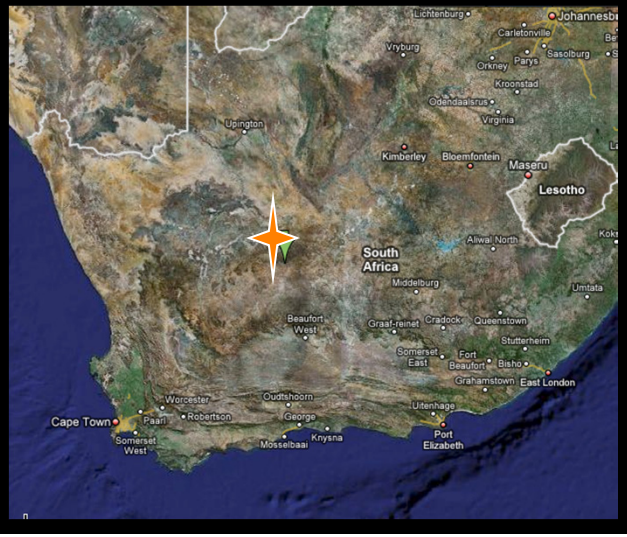
- ➢Locations of explosive or dynamic events
- ➢Probe fundamental physics and astrophysics
- Radio signals modified by, and are powerful probes of, intervening media
  - Dispersion
  - Scattering
  - Faraday rotation
- Media include
  - Interplanetary medium (IPM)
  - Interstellar medium (ISM)
  - Intergalactic medium (IGM)

An International Telescope

- Reference design
- "Preliminary Specifications for the SKA" (Schillizi et al. 2007)
- Technology development
  - U.S. TDP ($12M)
  - EC PrepSKA (EUR 5.5M + matching)

- System Requirements Review
  2008 January 29–30
- International Engineering Advisory Committee
  2009 April 29 – 30
- Siting
- SKA Forum





SKA Technology

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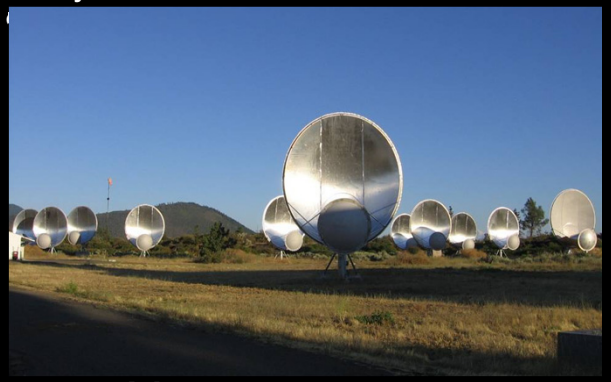
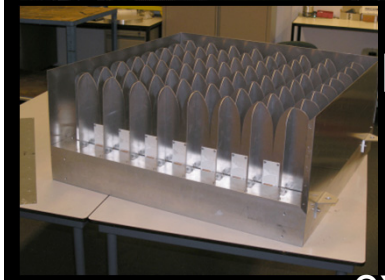


Novel antenna construction

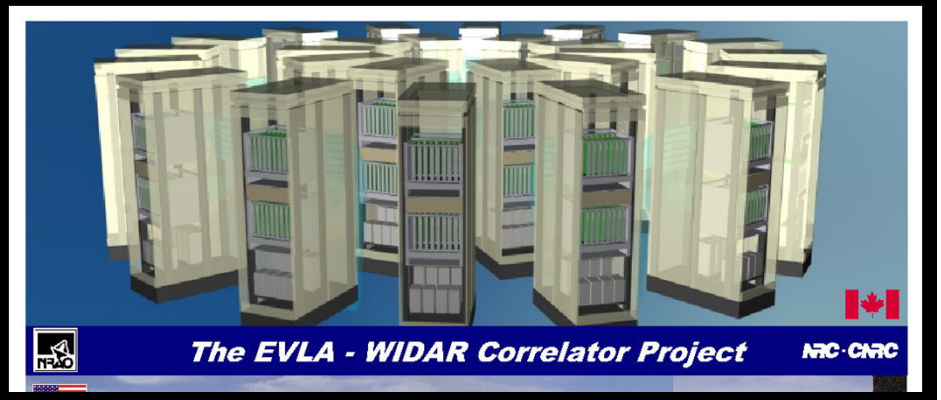
Fiber optic transmission

Ultra wide-band feeds



Phased arrays

(FoV expansion)



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SKA Pathfinding

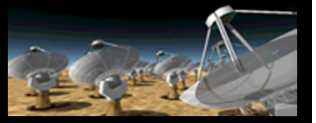
- Science pathfinding
- Novel antenna construction
- Sparse arrays
- Field of view expansion
- Wide-band feeds
- Signal transmission
- Processing and data management





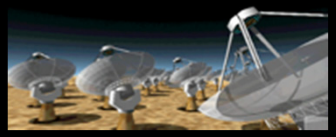


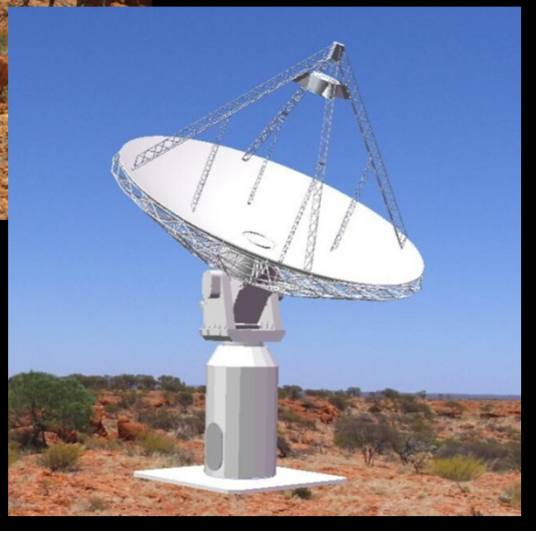





SKA Precursors





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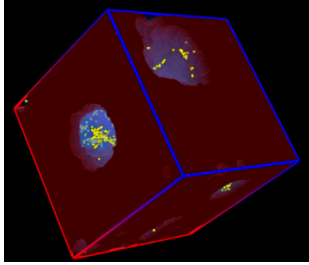
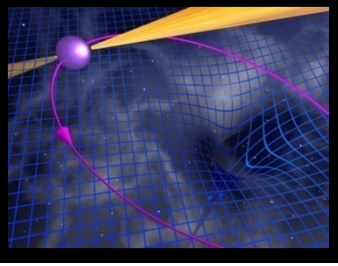
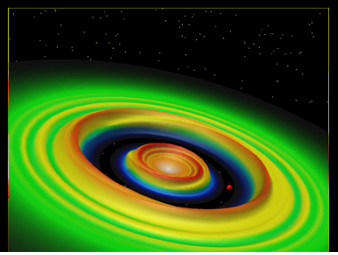
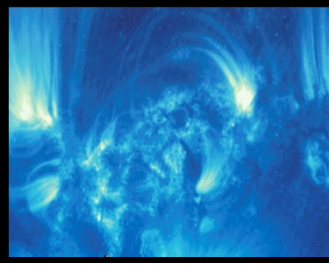
Square Kilometer Array
The Global Radio Wavelength Observatory

- Originally: "Hydrogen telescope"
  - Detect H I emission from Milky Way-like galaxy at $z \sim 1$
- SKA science much broader
  - $\Rightarrow$ Multi-wavelength, multi-messenger
- On-going technical development
- International involvement

Pushing to normal galaxies: spectral lines

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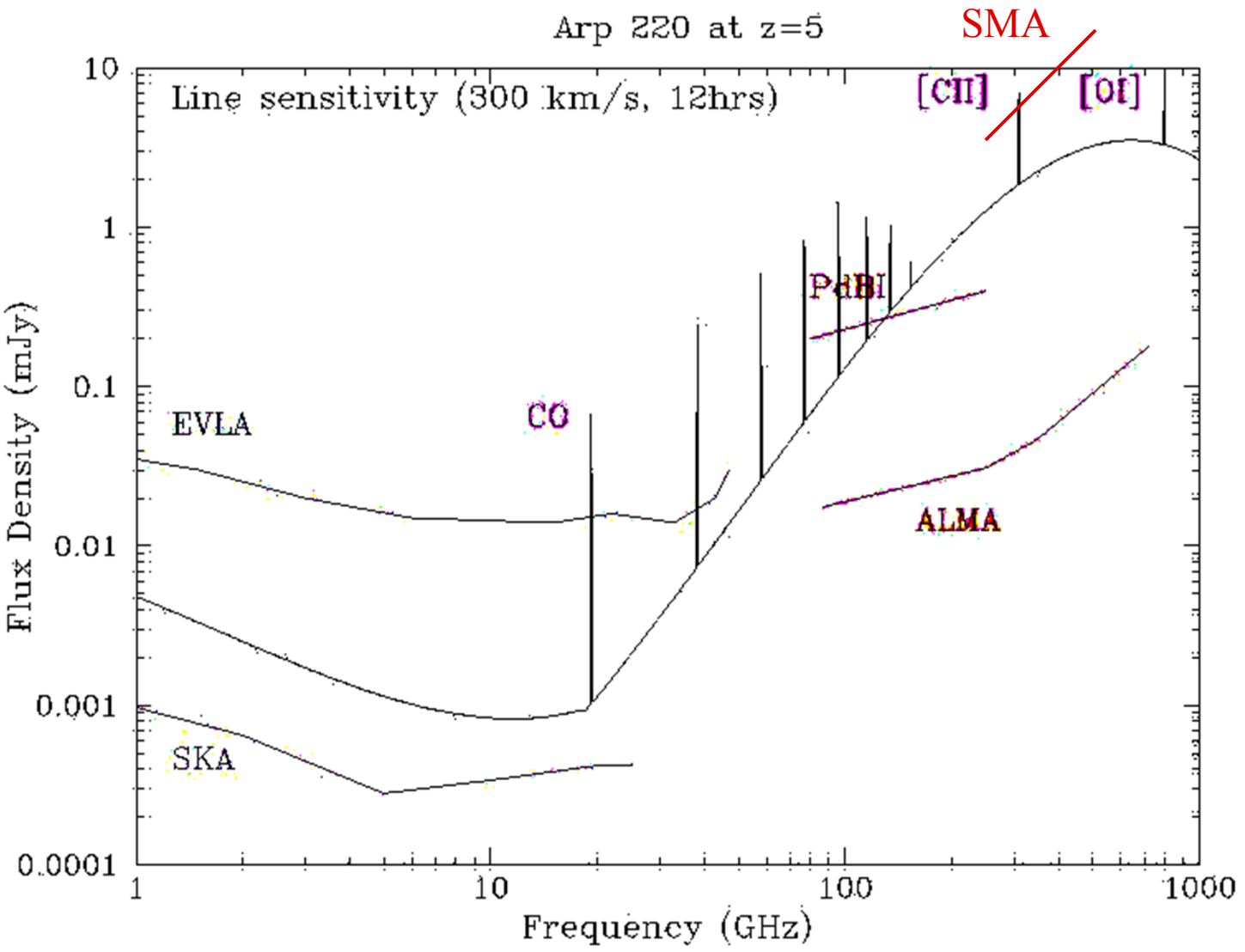

- FS lines will be workhorse lines in the study of the first galaxies with ALMA.
- Study of molecular gas in first galaxies will be done primarily with cm telescopes

Pushing to normal galaxies: continuum

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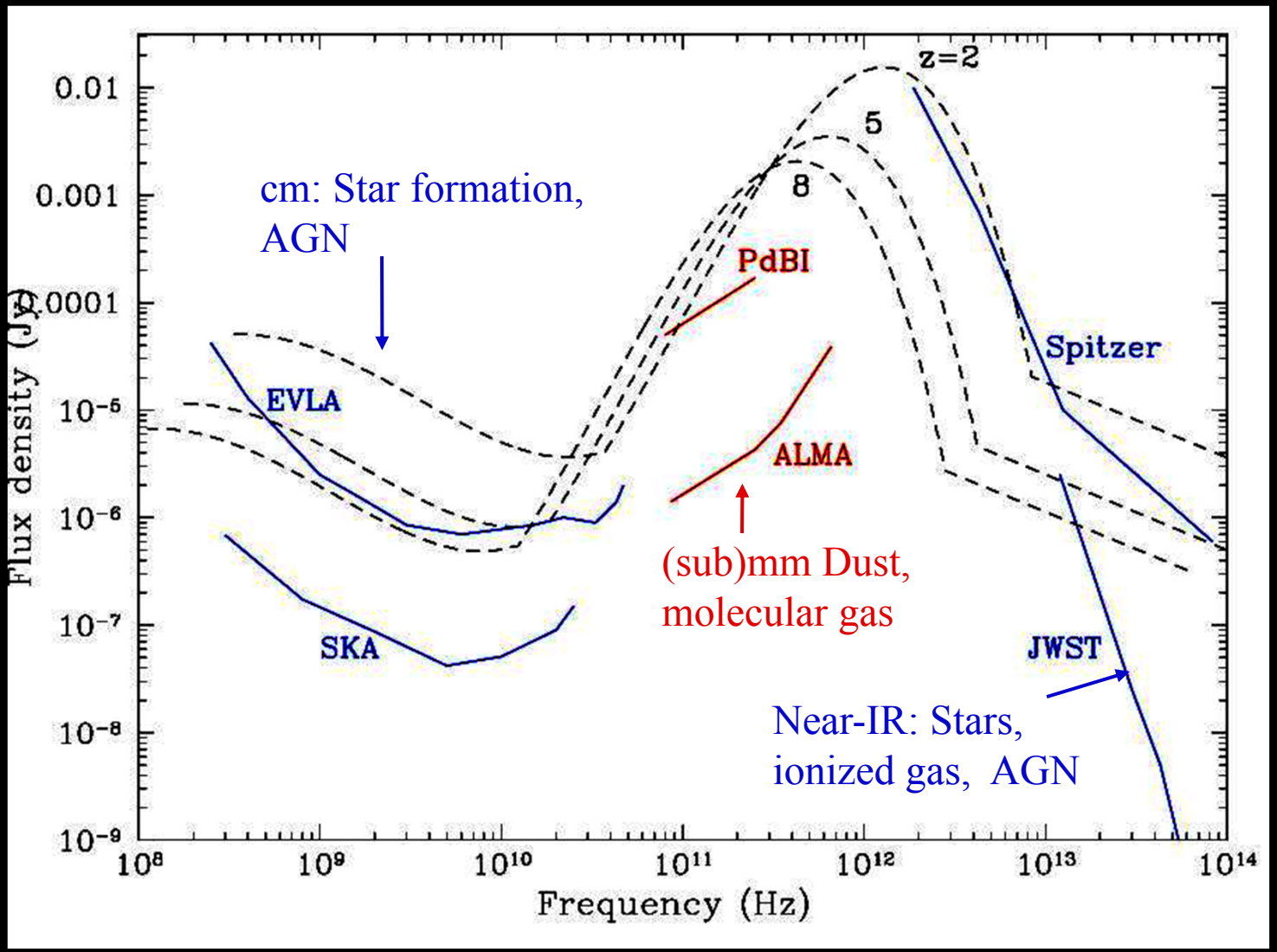
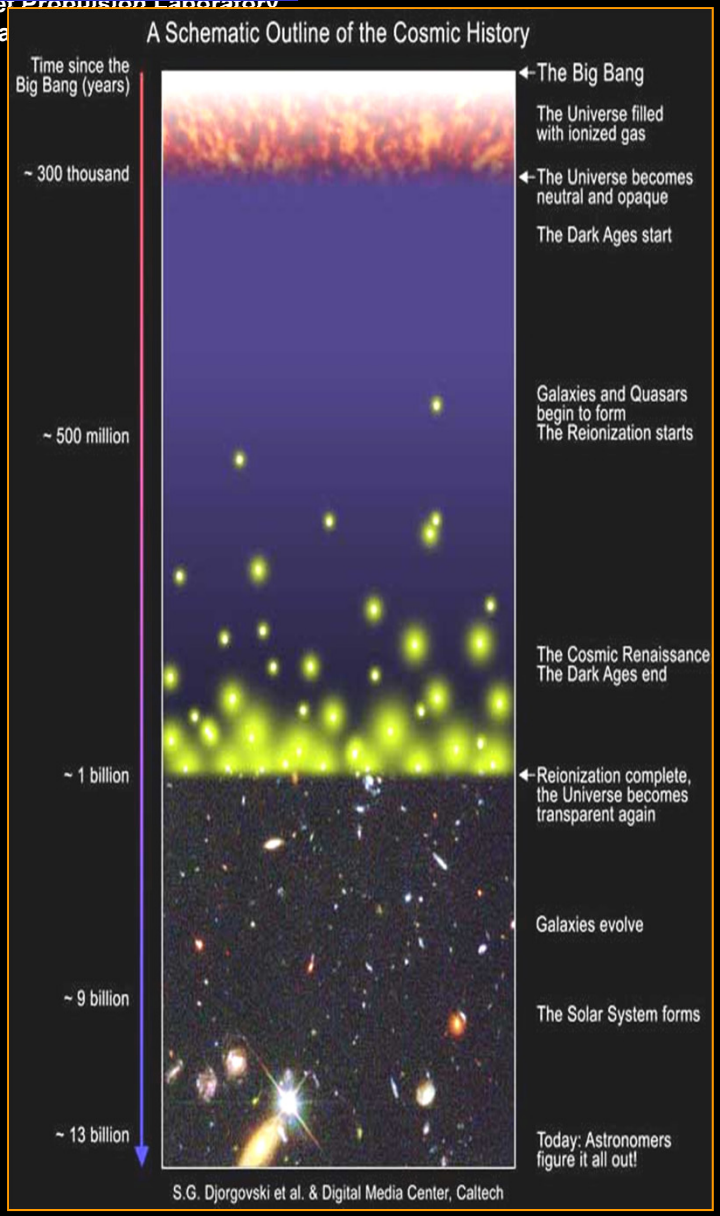
A Panchromatic view of galaxy formation

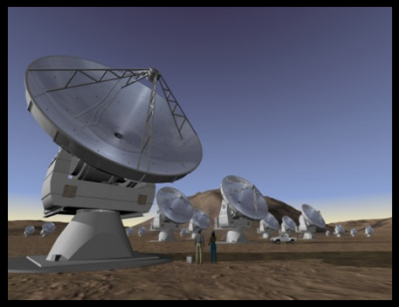


Origins
- First Light
- Galaxy Evolution
- Astrobiology

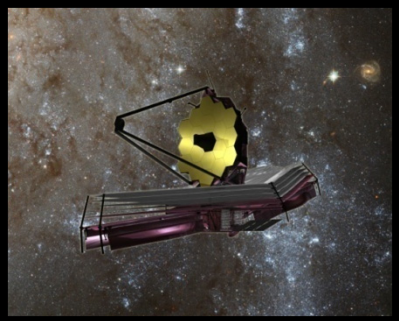
Epoch of Reionization



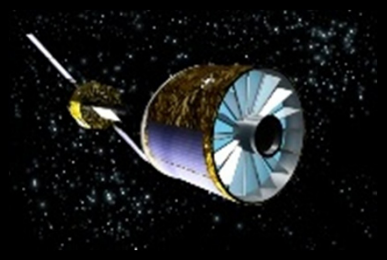
SKA: IGM and First Galaxies



ALMA: First Galaxies



JWST: First Stars and Galaxies



X-rays: First Black Holes

Origins
- First Light
- Galaxy Evolution
- Astrobiology

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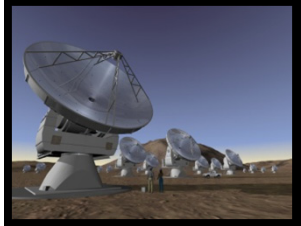
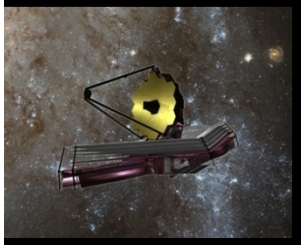
Galaxy Assembly & Evolution

SKA: atomic gas, star formation, feedback

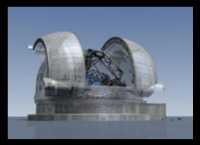


ALMA: molecular gas, star formation



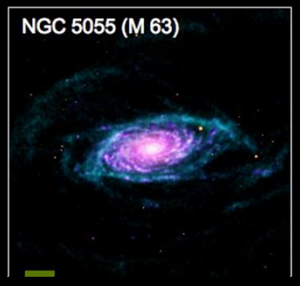
JWST: dust, star formation

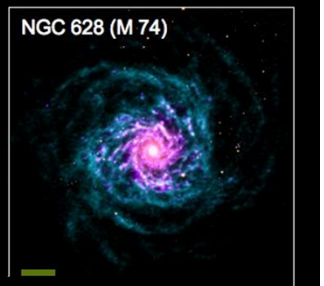


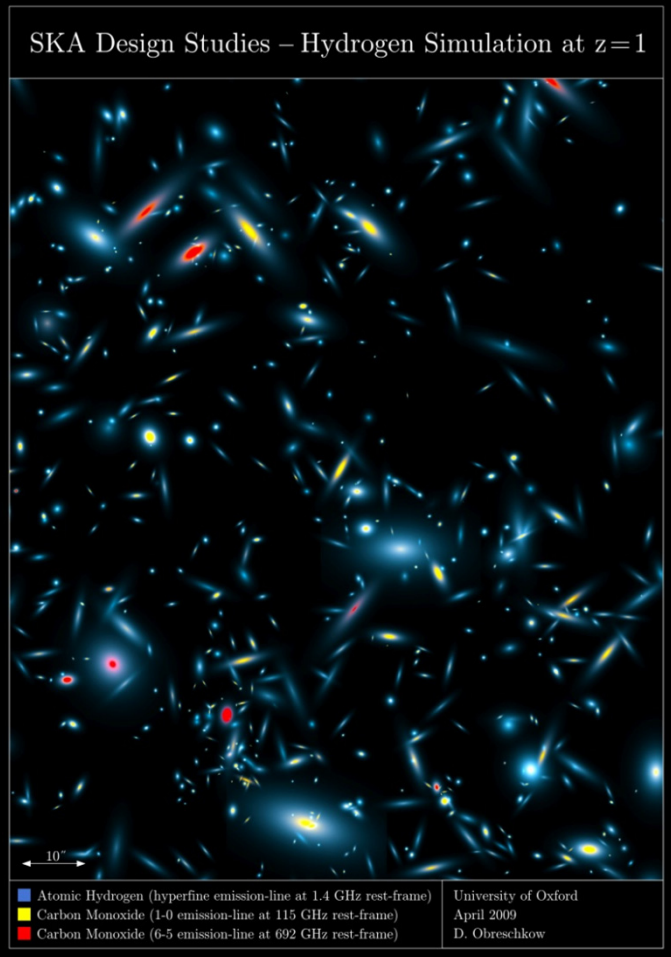


Optical/UV: stars, star formation

X- and γ-rays: feedback







Origins
- First Light
- Galaxy Evolution
- Astrobiology

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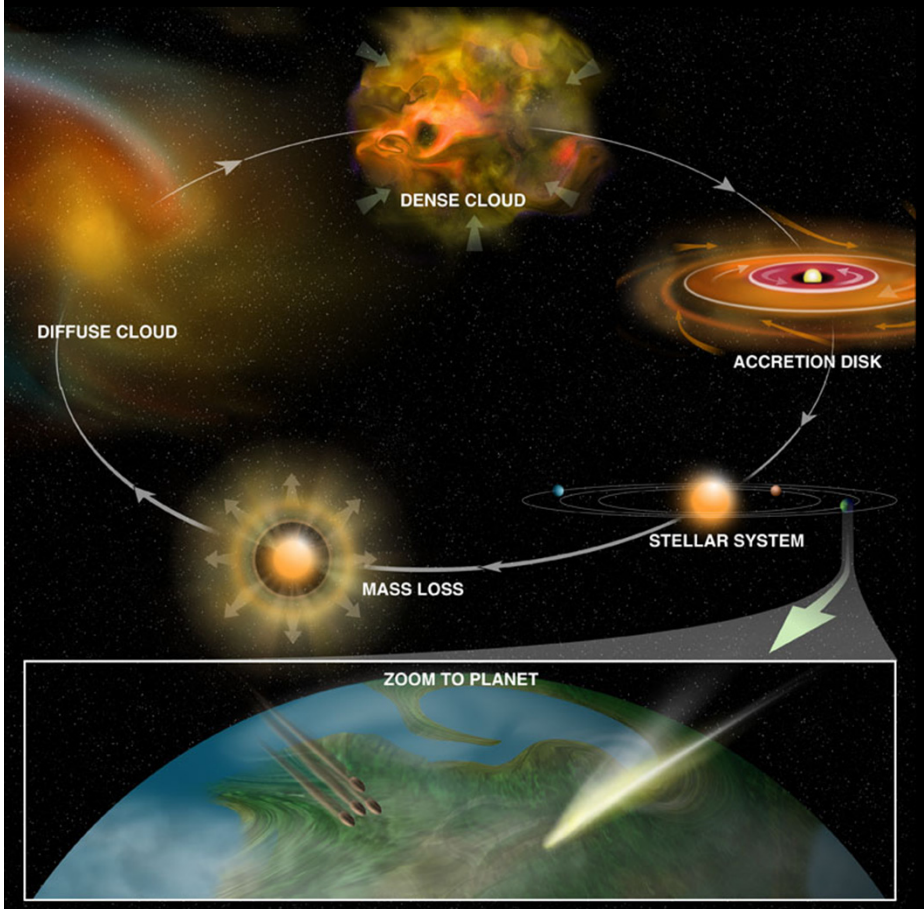
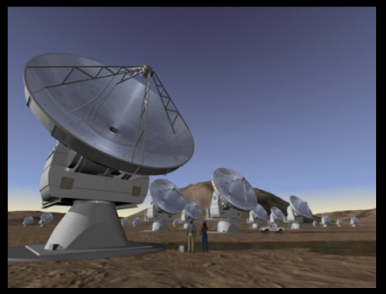
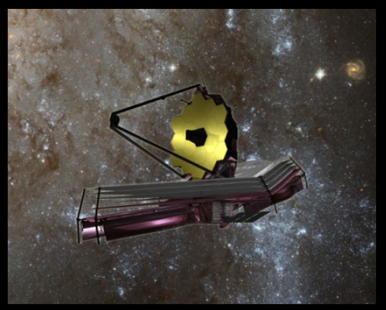
Astrobiology



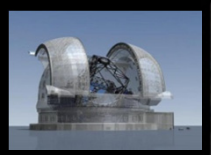
SKA: protoplanetary disks, molecules, planets, SETI



ALMA: protoplanetary disks, molecules



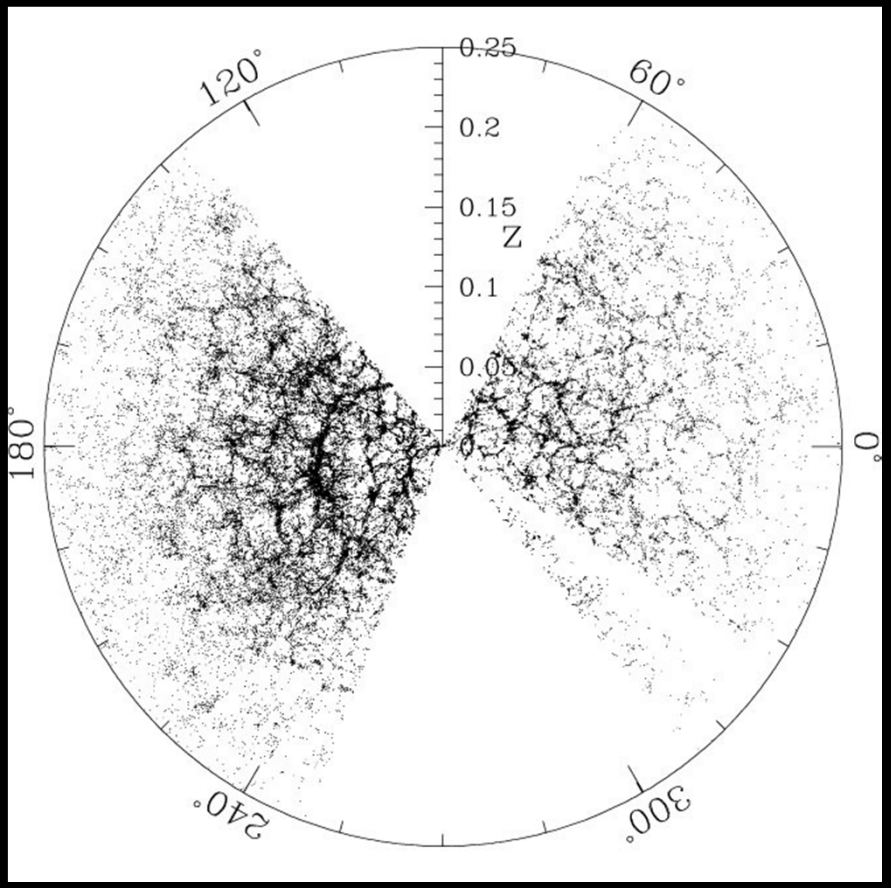
JWST: protoplanetary disks



Optical: protoplanetary disks, planets

Fundamental Physics
- Dark Energy
- GR & BHs
- Strong Force

SKA: Stage IV BAOs



SKA: H I BAOs ("Billion-Galaxy Survey")

LST: BAOs, supernovae, weak lensing, …

JDEM: supernovae, …